Submitted to Journal of Physics G

# The Future of Lepton-Nucleon Scattering
## a summary of the Durham workshop, December 2001

T. Greenshaw (Liverpool) and M. Klein (DESY-Zeuthen)

24th April 2002

A summary is given of the recent Durham workshop on the future of lepton-nucleon scattering. Discussions at the workshop centred on the need to ensure that an international scientific and technical programme is developed with the goal of further exploring the structure of the nucleon. Questions of particular interest include the investigation of nucleon structure and spin at extremely small Bjorken $x$. The role of the Electron Ion Collider in this programme was discussed, as was the necessity of ensuring that HERA is fully exploited.

## 1 The Situation - Open Questions after HERA2

HERA is currently scheduled to run until the end of 2006, the aim being to collect polarised $\overrightarrow{e}p$ scattering data corresponding to an integrated luminosity of 1 fb$^{-1}$ at the highest possible energy and to obtain some data at lower energy. This programme will allow exploration of proton structure at the smallest possible dimensions and will also produce large amounts of precision data at low Bjorken $x$. These data may result in the discovery of new effects at low $x$ or at high momentum transfers. In the latter case, the comparison of precision measurements with predictions from the QCD evolution equations, well understood in this kinematic regime, leads to sensitivity to the effects of large extra dimensions or contact interactions in the multi-TeV range. The production of new heavy particles, such as the squarks of $R$-parity violating supersymmetric theories, leptoquarks or excited fermions is also possible up to masses of about 320 GeV and the effects of these particles can be detected for masses significantly above this. The observation of novel effects with the envisaged five-fold increase in $e^+p$ and thirty-fold increase in $e^-p$ integrated luminosity would of course make further investigations beyond the year 2006 mandatory. Even if no new effects are discovered, the current HERA programme will leave a number of fundamental questions unanswered. Issues of prime importance are:

- What is the partonic structure of the neutron at low $x$, and at large $Q^2$ and $x$?

- What is the origin of confinement in long distance (small $x$) and short distance (large $x$) processes?
- How does the total deep inelastic scattering cross-section for lepton-proton and lepton-nucleus interactions change in the high density regime where cross sections may saturate and how are these changes reflected in the hadronic final state?
- How do the partons conspire to ensure that the spin of the nucleon is 1/2?

Understanding these problems will require data from lepton-deuteron and lepton-heavy ion scattering, as well as a programme of high energy and high luminosity colliding beam and fixed target experiments involving polarised leptons, polarised protons and polarised deuterons. In addition to addressing the above questions, this programme will be vital to our understanding of the astrophysical significance of extremely high-energy neutrino scattering, as well as being necessary to ensure full exploitation of the physics potential of the LHC and of heavy ion collisions.

The Durham meeting brought together about 40 physicists, including the Spokespersons, Physics and Technical Coordinators of the HERA experiments H1, ZEUS, and HERMES, of COMPASS at CERN, leaders of the Electron-Ion Collider (EIC) Community and leading machine and theory experts. The programme of the workshop (available at http://hep.ph.liv.ac.uk/∼green/HERAfuture) comprised sessions devoted to the current HERA programme (HERA2), QCD, polarised $\ell N$ physics, detectors, deuterons and heavier nuclei and machine developments at HERA and the EIC. It ended with an extended discussion about the plans, options and prospects for future deep-inelastic scattering experiments prior to the operation of TESLA.

## 2 Physics Subjects - Nuclei and Polarisation

Much of the physics of nuclei and polarisation has been studied at previous workshops, and frequent reference was made to the HERA $eA$ workshops [1], to the HERA spin workshops [2], to the EIC white book [3], to the THERA book [4], to the TESLA-N [5] and to the ELFE [6] proposals.

As mentioned above, after completion of the currently approved HERA programme, there will be a continued interest in precision measurements in the low $x$ region. This concerns in particular the measurement of jets very close to the proton beam direction, crucial to the understanding of the emission of gluons at low $x$, and the kinematic region in which $Q^2 \sim 1$ GeV$^2$, where the energy dependence of the $\gamma^* p$ cross-section becomes hadron-hadron like. Precision inclusive and exclusive cross-section measurements in this kinematic region may yield insight into saturation physics and the confinement problem. This programme will require that the instrumentation in the forward and backward regions very close to the beam pipe at HERA be upgraded, that efficient proton tagging is possible and that the beam divergence is small.

Electron-deuteron scattering appears to be the natural next step at HERA following the $ep$ programme. Deuterons are a source of quasi-free neutrons, measurements of which are perturbed slightly in the region $x < 0.1$ by nuclear shadowing effects. These latter are related to the diffractive parton densities and hence the effects of shadowing on lepton-deuteron cross-sections can be determined to an accuracy of better than 1-2%. The quark distribution asymmetry, $(u + \overline{u}) - (d + \overline{d})$, can thus be accurately measured from the difference $F_2^p - F_2^n$. Deuteron data are also essential for determining the individual flavour decomposition of the nucleon parton distributions at large $x$, allowing measurement of quantities such as $s - c$ or the $d/u$ ratio, as well as for determining charged current structure functions and for precision tests of $Q^2$ evolution in perturbative QCD.

The rise of the proton structure function $F_2$ towards low $x$ in the deep-inelastic scattering region is due to the high sea quark density in the proton. This is related to the gluon distribution $xg \propto \partial F_2/\partial \ln Q^2$, which also rises as $x^{-\lambda}$ towards low $x$, with $\lambda \approx 0.1 \ldots 0.4$ for $Q^2 \approx 1 \ldots 100$ GeV$^2$. Since $xg$ is expected to increase with atomic number $A$ as $A^{1/3}$ (modulo shadowing effects), electron-nucleus scattering allows an equivalent Bjorken $x = x_N/(A^{1/3})^{1/\lambda}$ to be accessed: such collisions can thus be used to investigate a kinematic regime which in $ep$ scattering would require a considerable increase in the centre-of-mass energy. Diffractive processes may constitute up to 50% of the inclusive lepton-nucleus cross section, the maximum value allowed by unitarity considerations. Such an observation would represent an unambiguous signal for a new regime in deep-inelastic scattering. Since the contribution of small-size configurations to diffraction goes as the square of $xg$, non-linear effects which damp the growth of the total cross-section may first be seen in diffraction. The nucleus is widely considered to be an ideal laboratory for deconfinement and high density QCD analyses.

It is envisaged that spin physics with fixed polarised targets will be continued at DESY beyond 2006 with a high luminosity measurement programme. With modest improvements to the HERMES apparatus, high resolution experiments with increased luminosity will become possible. Such measurements will be devoted to a detailed study of exclusive reactions, in particular deeply virtual Compton scattering, and will lead to the first precise experimental information on generalised parton distributions.

Collisions of beams of polarised electrons and polarised nucleons will make possible the first investigations of spin phenomena at high $Q^2$ and at low $x$. These will be enhanced by the comprehensive reconstruction of the final state possible in colliding beam experiments. The behaviour of the spin structure function $g_1(x, Q^2)$ at low $x$ is unknown, but it is expected to change even more dramatically than $F_2$. The $Q^2$ dependence of $g_1$ determines the gluon spin distribution $\Delta G$, one of the components of the spin of the proton. Semi-inclusive measurements can be used to explore the flavour structure of spin: dijets give access to $\Delta G$ and deeply virtual Compton scattering to the generalised parton distributions. Photoproduction processes give insight into the polarised gluonic structure of the photon and diffractive polarised scattering into pomeron exchange. Beyond the fixed target $\overrightarrow{e}\overrightarrow{p}$ domain, there is a vast unexplored kinematic region and polarised colliding beam experiments may radically change our view on the spin structure of the nucleon.

# 3 Detector Aspects

The status and upgrade plans for H1, ZEUS and HERMES at DESY, and COMPASS at CERN were summarised by the technical coordinators of these experiments. It was pointed out that in 2006 the HERA collider detectors will be 15 years old. Continued operation will require some detector and electronics upgrades. For example, whereas the H1 liquid argon calorimeter has proved to be extremely stable, in all probability an upgrade to the central tracking facilities will be necessary, including replacement and possibly extension of the silicon detectors. More accurate judgements on the long-term prospects for operation of the H1 and ZEUS detectors will be possible following the first years of high luminosity running at HERA2.

Currently, the HERA interaction regions are optimised for high luminosity running, with focussing magnets placed close to the interaction region. This sets a limit on the minimum measurable four-momentum transfer squared of about 4 GeV$^2$. These high luminosities are essential for the measurement of small spin-induced asymmetries and also for high statistics $eD$ measurements. At low $Q^2$, event rates will be high and substantial upgrades of the front-end electronics may be required.

For accessing the region around $Q^2 = 1$ GeV$^2$ and the smallest $x$ values in $eA$ scattering, it will be necessary to return to an arrangement which leaves room for new or upgraded detectors close to the beam pipe. An essential requirement for diffractive measurements and for deuteron spectator tagging is large acceptance forward nucleon tagging.

It is expected that the HERMES detector, perhaps with some upgrades to the data acquisition system and silicon detectors, will be able to run beyond 2006. The COMPASS experiment uses a variety of modern detector technologies which may be of use for future HERA3 detectors.

# 4 Accelerators - HERA and the EIC

Following the recent upgrade, HERA is scheduled to run with a luminosity of $7 \times 10^{31}$ cm$^{-2}$s$^{-1}$ until the end of 2006. The maximum attainable luminosity is estimated to be $13 \times 10^{31}$ cm$^{-2}$s$^{-1}$. This corresponds to an annual integrated luminosity of about 500 pb$^{-1}$, making the measurement of small asymmetries at low $x$ in polarised $\overrightarrow{e}\overrightarrow{p}$ scattering statistically feasible if intense polarised proton sources can be constructed. Precise measurements require a high degree of polarisation which must be transferred through the accelerator chain, necessitating the use of Siberian Snakes. Polarimeters allowing accurate polarisation measurements are also essential. The small anomalous magnetic moment of the deuteron may make realisation of polarised $\overrightarrow{e}\overrightarrow{D}$ collisions easier than the $\overrightarrow{e}\overrightarrow{p}$ case using a scheme which relies on resonant driving of the spin using horizontal RF fields.

Pilot $eA$ scattering studies can be performed using deuterium, oxygen and calcium. Light ions can be accelerated in HERA with moderate modifications to the accelerator

chain. Electron cooling becomes necessary if heavier nuclei are to be accelerated to counter intra-beam scattering (IBS) effects. The luminosity is then expected to scale as $L_A \simeq L_p/A$. For deuterons, the IBS time exceeds two hours and a luminosity of $3.5 \times 10^{31}$ cm$^{-2}$s$^{-1}$ may be achieved without cooling. Thus, high luminosity $eD$ running can be realised immediately after completion of the HERA2 programme and requires no major modifications to HERA beyond the necessary changes to the source.

The EIC, formal proposals for which are expected to be presented in about 2005, will be an intense polarised electron-ion collider using electron beam cooled ions in RHIC (of up to $E_p = 250$ GeV proton and $E_{Au} = 100$ GeV/A gold energy) colliding with electrons from a ring or linear accelerator of about 10 GeV maximum energy. Thus the EIC has 10 times less centre-of-mass energy than HERA, but due to its high luminosity it greatly extends the range of current polarised fixed target experiments, and with heavy nuclei allows access to high parton densities. The ring-ring accelerator has an estimated luminosity of 25 (0.7) $\times$ $10^{31}$ cm$^{-2}$s$^{-1}$ for protons (gold), which is comparable to HERA after run 2. With an energy recovery linac, it is expected that a still higher luminosity of 100 (1.0) $\times$ $10^{31}$ cm$^{-2}$s$^{-1}$ for protons (gold) may be obtained. The linac, while accelerating $e^-$ only, has the further advantage of providing high polarisation and avoiding synchrotron radiation background.

# 5 Conclusions and Outlook

If answers are to be found to the questions posed in the introduction, three experimental programmes must be pursued:

- Electron-deuteron scattering experiments, with both high luminosity (more than 100 pb$^{-1}$) and detectors that have dedicated low $x$ and forward nucleon tagging capability.
- Extended measurements at low $x$: studies of the problems of confinement require precision diffractive and non-diffractive data at $Q^2$ near to 1 GeV$^2$; high density gluon effects leading to saturation may be studied in electron-nucleus scattering.
- High luminosity polarised $\overrightarrow{e}\overrightarrow{p}$ and $\overrightarrow{e}\overrightarrow{D}$ scattering: spin physics requires further operation of fixed target experiments and the investigation of the unknown world of low $x$ and high $Q^2$ deep-inelastic spin phenomena using collider detectors.

Work in the coming years will be directed towards producing proposals for the operation of HERA beyond 2006 and for the EIC which may start operation in 2012, after completion of the polarised proton phase of RHIC. A programme will be devised which produces maximum physics return from HERA and the EIC, with their complementary reach in energy, luminosity and nuclear mass. An extension by another order of magnitude in energy in $ep$ scattering can be achieved with THERA, the future $ep$ collider operating at TeV energies.

6 Acknowledgements

The authors would like to thank the DESY Directorate and the Institute for Particle Physics Phenomenology for their support and Linda Wilkinson and the other members of the organising committee for helping to arrange what proved to be a most interesting and productive meeting, namely Jochen Bartels, Alan Martin, Martin McDermott, Klaus Rith, Jim Whitmore, Ferdinand Willeke and Giulia Zanderighi. This summary has benefited from the suggestions of Allen Caldwell, Eckhard Elsen, Robert Klanner, Alan Martin, Martin McDermott, Dirk Ryckbosch, Peter Schleper, Mark Strikman and Ferdinand Willeke. We would also like to thank the representatives of the theory community and the COMPASS, HERMES, H1 and ZEUS Collaborations who contributed to the workshop.

# References

[1] http://www.desy.de/heraea, "Physics with HERA as Electron-Nucleus Collider", Ed.s G. Ingelman and M. Strikman, May 1999;
http://www.desy.de∼heraws96, "Future Physics at HERA", Proc. Workshop, DESY 1996/97, Ed.s G. Ingelman, A. De Roeck and R. Klanner, pp 854-1092.

[2] "Prospects for Spin Physics", Proc. Workshop, Ed.s J. Blümlein and W.D. Nowak, DESY 95-200, Zeuthen 1995;
"Physics with polarized protons at HERA", Proc. Workshop, Ed.s A. De Roeck and T. Gehrmann, DESY-PROC-1998-01, Hamburg 1997;
http://www-h1.desy.de∼radel/spin99/procsent.html, "Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities", Proc. Workshop, Ed.s A. De Roeck, D. Barber and G. Rädel, DESY-PROC–1999–03 (1999), Hamburg 1999;
"The Spin Structure of the Proton and Polarized Collider Physics", S.D. Bass and A. De Roeck, Nucl. Phys. Proc. Suppl. **105** 1-27 (2002);
"Transverse Spin Physics", Workshop transparencies, DESY-ZEUTHEN-01-01, 374 pp, Zeuthen 2001.

[3] http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC, "The EIC White Book", R. Holt et al., BNL, March 2001.

[4] http://www-zeuthen.desy.de/thera, "THERA: Electron-Proton Scattering at $\sqrt{s} \sim 1$ TeV", TESLA TDR, DESY 2001-011, ECFA 2001-209, part VI, Appendices, pp. 99-160, Ed.s R. Klanner, U. Katz, M. Klein and A. Levy, March 2001;
"The THERA Book", Ed.s U. Katz, M. Klein, A. Levy and S. Schlenstedt, DESY-01-123, DESY-01-123-F, LC-REV-2001-062, DESY-LC-REV-2001-062, Dec 2001, 415 pp.

[5] "TESLA-N: Electron Scattering with Polarised Targets at TESLA", TESLA TDR, DESY 2001-011, ECFA 2001-209, part VI, Appendices, pp. 161-190, Ed.s R. Klanner, R. Kaiser and W.D. Nowak.

[6] "ELFE: The Electron Laboratory for Europe", TESLA TDR, DESY 2001-011, ECFA 2001-209, part VI, Appendices, pp. 191-207, Ed.s R. Klanner, E. DeSanctis, J.-M. Laget and K. Rith.